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Western Washington Office
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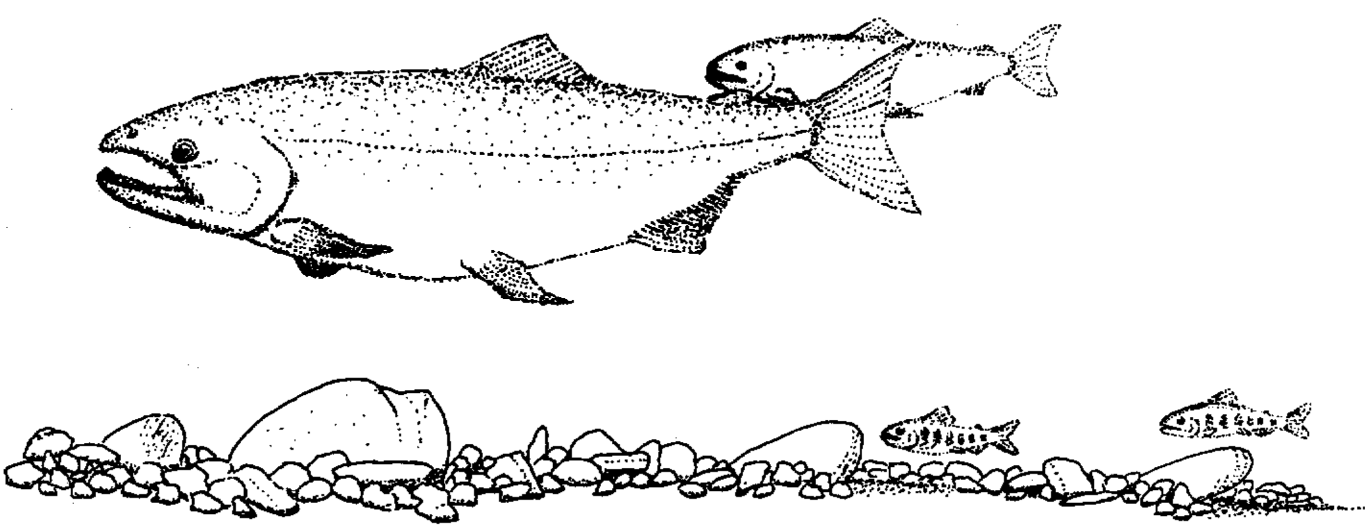

The Importance of Estuarine Habitats to Anadromous Salmonids of the Pacific Northwest: A Literature Review

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In cooperation with:
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Preface

The purpose of this report is to provide information on anadromous salmonid utilization of estuaries in the Pacific Northwest. This report reviews the literature produced from 1979 to present. For a review of the literature before 1979 please refer to Meyer (1979). The reader should consider this review a continuation of Meyer's report.

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INTRODUCTION

The importance of estuaries to anadromous salmonids has been well reviewed in the past (Iwamoto and Salo 1977; Dorcey et al. 1978; Meyer 1979; Shepard 1981; Hiss and Boomer 1986; Thorpe 1994), but this author was unable to find any review articles since 1994. This report will review the literature produced since Meyer's (1979) literature review. The catalyst for this report was the need to provide up-to-date information on salmonid utilization of estuarine habitat at the Nisqually National Wildlife Refuge.

Under the direction of the 1997 National Wildlife Refuge (NWR) Improvement Act, Nisqually NWR staff are preparing a Comprehensive Conservation Plan (CCP) for the refuge. The CCP process provides a 15-year plan to guide refuge management. Issues of land acquisition, wildlife dependent recreation, public access, and habitat management/restoration are some of the major topics to be addressed by the CCP.

Development of a CCP for Nisqually NWR provides an important opportunity to investigate the feasibility, habitat benefits, and economic costs of restoring intertidal habitat by breaching dikes. In addition to these general ecological benefits, this process has the potential to significantly benefit salmon, depending on the alternative pursued. This is an especially important outcome, given the likelihood that Puget Sound chinook salmon may soon be listed under the Federal Endangered Species Act. While qualitative information can be provided with existing information, more substantiated quantitative information on intertidal restoration will require additional research.

Estuarine habitat comprises only 10%-20% of the Pacific coast and a large percentage has been lost to diking, channelization, and dredging and filling (Burg 1984). Burg (1984) reported that California has lost approximately 65%, Oregon has lost approximately 80%, the Columbia River has lost approximately 24%, and Washington has lost between 45% and 62% of their respective pre-settlement estuarine habitat. In some cases individual estuaries in Washington have lost up to 100% of the pre-settlement habitat (Simenstad et al. 1982; Schmitt et al. 1994). Bortelson et al. (1980) estimate that in the Nisqually River estuary, approximately 4.1 km^2 of the historical 5.7 km^2 of subaerial wetlands (area above mean high-water line) remain, for a loss rate of 28%. In addition, approximately 5.8 km^2 of the historical 7.4 km^2 of intertidal wetlands (area between mean high-water line and mean lower low-water line) remain, for a loss rate of 22%.

There are eight species of native anadromous salmonids occurring in the Pacific Northwest. They are chinook salmon (*Oncorhynchus tshawytscha*), chum salmon (*O. keta*), pink salmon (*O. gorbuscha*), coho salmon (*O. kisutch*), sockeye salmon (*O. nerka*), steelhead (*O. mykiss*), sea-run coastal cutthroat trout (*O. clarki clarki*), and sea-run Dolly Varden char (*Salvelinus malma*). This report will primarily examine the utilization of estuaries by the first five species listed, as most information collected concerns them. This information includes the usage of estuaries by juvenile anadromous salmonids as rearing areas, as refugia, and as transition areas.

The objective of this report is to provide estuarine land managers with basic information on salmonid utilization of estuaries, and assist them in making educated restoration decisions. The geographic focus of this review is western Washington, although literature and information were drawn from a variety of sources throughout the Pacific Northwest.

METHODS

The literature search consisted of information collected from libraries, abstract databases, miscellaneous files, and personal communication. The University of Washington Libraries, The Evergreen State College Library, St. Martin's College Library, and The Washington State Library were all searched via the Internet. The two abstract databases used were the Aquatic Sciences and Fisheries Abstracts (ASFA) and BIOSIS, both available at the University of Washington Libraries. The U.S. Fish and Wildlife Service's Fish and Wildlife Reference Service was also searched. Both the library and miscellaneous employee files at the Western Washington Office of the U.S. Fish and Wildlife Service were examined, in addition to office files at the Nisqually National Wildlife Refuge. Regional researchers working on this issue were also contacted and assisted in filling any gaps left from the initial search.

DISCUSSION

Salmonid Utilization of Unaltered Estuaries

Due to their anadromous life cycle, salmon pass through estuaries as adults on their upstream migration to spawn and as juveniles on their downstream migration to the ocean (Healey 1982). Estuaries are very important to adult salmon for staging and physiological transition, and to juvenile salmon for foraging, physiological transition, and refugia (Healey 1982; Levy and Northcote 1982; Iwata and Komatsu 1984; Miller 1993; Thorpe 1994).

<u>Chinook</u>

Chinook have been found to occur in two life history "types" — the "stream type" and the "ocean type" (Myers et al. 1998). The stream type spends one or more years as fry or parr in fresh water before migrating to salt water. The ocean type, which is the common type south of 56° N latitude, spends less than a year (as little as three months) in fresh water before migrating to salt water (Healey 1991). Due to the different types, juvenile chinook salmon typically arrive at the estuary at three different times in their life cycle. Chinook may enter the estuary immediately after emergence as fry from March to May at a length of 40 mm; they may enter the estuary as fingerling smolts during May and June of their first year at a length of 60-80 mm; or they may not enter the estuary until April and May of their second year as yearling smolts at a length of 80-110 mm (Healey 1982).

Ocean-type chinook salmon use estuaries as rearing areas, and of all chinook "types" as well as other species of salmon, are most dependent on estuaries to complete their life cycle. Depriving migrating juvenile chinook access to estuarine habitat appears to decrease their overall survival (Macdonald et al. 1988). Chinook fry have been observed living in estuaries with salinities up to 15-20 ppt (Healey 1991). Resident juvenile chinook salmon move with the tide, but attempt to stay at the leading edge of the water (Levy and Northcote 1982). On the flooding tide the juvenile fish move into the marshes at the highest reaches of the tide (Healey 1991). On the ebbing tide the fish recede into tidal channels that retain water at low tide (Healey 1991). There appears to be a seasonal redistribution of juvenile chinook in both the Vancouver Island estuaries and the Sacramento-San Joaquin estuary. As waters warm larger fish appear to prefer deeper water than the smaller fish and are able to live at higher salinities than the smaller fish (Kjelson et al. 1982; Healey 1991). Juvenile chinook begin to migrate from estuaries at about 70 mm fork length (Healey 1980; Kjelson et al. 1982; Healey 1991; Hayman et al. 1996). Coded-wire-tag recovery data from juvenile hatchery chinook salmon captured at the Nisqually River estuary indicated that juvenile anadromous salmonids also utilize non-natal estuaries (Pearce et al. 1982).

Chum

Chum are second only to chinook in dependence upon estuaries as rearing areas (Salo 1991; Johnson et al. 1997). Chum fry start moving downstream toward the estuary of their natal stream immediately after emergence (Healey 1982; Salo 1991). The fry usually reach the estuary within a few days at a length of 30-40 mm between March and May (Healey 1982; Simenstad et al. 1982). Chum do not appear to school as much as pink or sockeye fry. Chum fry residing in estuaries occupy tidal creeks, sloughs, and marshes. Like chinook, chum also congregate at the upper intertidal fringes of marshes at high tide, and they retreat to tidal creeks with flowing water at low tide (Healey 1982). The favored low tide habitat of chum fry is the junction of major and minor distributaries of river deltas (Healey 1982).

Pink

Pink salmon fry, like chum salmon fry, also migrate downstream directly after emergence and arrive at the estuary at a length of 30-40 mm between March and May (Healey 1982; Simenstad et al. 1982; Hard et al. 1996). Pink salmon fry have both a tendency to school and an affinity for salt water. Heard (1991) reported that pink fry in Alaska were found feeding in estuaries for up to two months, but usually pink fry go directly to the ocean and rear in shallow shoreline areas.

Coho

Coho, like chinook, also occur in two life history "types" — a "stream type" and an "ocean type" (Tschaplinski 1982, 1987). The stream type spends one or more years as fry or parr in fresh water before migrating to salt water (Healey 1982). Yearling stream-type coho smolts usually arrive at the estuary of their natal stream between April and June at a length of 60-100 mm (Healey 1982; Simenstad et al. 1982). The ocean type, which are more commonly found in small estuaries, spends less than a year (as little as one week) in fresh water before migrating to salt water (Tschaplinski 1987). Ocean-type coho fry enter the estuary in early spring (March to April), soon after emergence (Tschaplinski 1982, 1987) and may comprise up to 30% of a year class in a local population (Tschaplinski 1982, 1987; Nielsen 1994). Ocean-type coho have been found to comprise up to 50% of the adult spawners returning to Porcupine Creek, Alaska (Tschaplinski 1987).

Sockeye

Sockeye salmon occur in three life history "types" — the "lake type," the "river type," and the "sea type" (Gustafson et al. 1997). The lake type spends one to three years rearing in lakes before migrating to salt water. Lake-type sockeye smolts usually arrive at the estuary from April to June at a length of 60-100 mm (Healey 1982; Simenstad et al. 1982). The river type spends one to two years rearing in the lower, slow-velocity sections of rivers before migrating to salt water. The sea type spends only a few months in rivers before migrating to salt water and rearing in estuaries. River- and sea-type sockeye salmon have not been reported south of the Fraser River, British Columbia, whereas lake-type sockeye are reported throughout the Pacific coast (Healey 1982; Burgner 1991; Gustafson et al. 1997). In the Fraser River system, a small portion of sockeye fry migrate downstream as fry and rear in the Fraser River Delta for up to five months (Burgner 1991).

Steelhead, Coastal Cutthroat, and Dolly Varden Char

A summary of the anadromous forms of the remaining species follows. Steelhead pass through estuaries during migration as both smolts and adults, but do not appear to use estuaries for rearing (Emmett et al. 1991). Most anadromous cutthroat trout smolts and adults pass through estuaries during migration and inhabit coastal neritic waters (Emmett et al. 1991). However, some anadromous cutthroat trout, both smolts and adults, reside in estuaries and feed mainly on outmigrating salmonid fry (Miyamoto et al. 1980; Trotter 1987; Emmett et al. 1991; Thorpe 1994). Dolly Varden char pass through estuaries while migrating, similar to steelhead (Wydoski and Whitney 1979) and inhabit coastal neritic waters, like cutthroat (Thorpe 1994).

Foraging and Evidence of Growth in Estuaries

All five species of salmon have been found to feed in estuaries and their diets are geographically, seasonally, and annually variable (Healey 1982). The highest juvenile growth rates for some species of salmon (specifically chinook and chum) have been recorded in estuaries (Simenstad et al. 1982). Therefore, juvenile salmonids rearing in estuaries may enter the marine environment at a larger size than conspecifics rearing in rivers; this may increase their marine survival (Kjelson et al. 1982; Wissmar and Simenstad 1988).

Chinook

Juvenile chinook salmon diet in the Sacramento-San Joaquin estuary was dominated by dipterans, cladocerans, copepods, and amphipods (Kjelson et al. 1982). Chinook fry from Washington estuaries fed on emergent insects and epibenthic crustaceans (gammarid amphipods, mysids, and cumaceans) in salt marsh habitat, but preyed on decapod larvae, larval and juvenile fish, drift insects, and euphausiids as they grew and moved into neritic habitats (Simenstad et al. 1982). In the Nisqually River estuary, insects of the order Diptera and spiders were the dominant prey of small chinook (61 mm - 70 mm in length), but as the fish grew (71 mm - 90 mm in length), opossum shrimp *(Neomysis mercedis)* and cumaceans *(Cumella)* became the dominant prey (Pearce et al. 1982). Chinook from the Nanaimo estuary fed on decapod larvae, mysids, adult insects, and then preyed on larval herring (*Clupea harengus pallasi*) as they moved to higher salinity waters (Healey 1982).

Kjelson et al. (1982) compared the growth of chinook salmon fry rearing in the Sacramento-San Joaquin estuary to chinook fry rearing in the upper Sacramento River in 1981. They found that the fish rearing in the estuary had an average growth of 0.53 mm day^{-1} versus 0.33 mm day^{-1} for the fish rearing in the river. Congleton et al. (1982) reported that chinook rearing in the Skagit River estuary were, on average, larger than their respective river-rearing conspecifics. These data suggest that chinook fry rearing in estuaries grow faster than conspecifics rearing in upper river habitat, and that estuaries are well utilized by chinook fry. Wild chinook salmon were also found to rear in Yaquina Bay, as indicated by their increase in size and their protracted residence (Myers and Horton 1982). Juvenile chinook in the Nanaimo estuary grew approximately 5.5% of their body weight per day (Healey 1982). Chinook rearing in the Fraser River estuary also exhibited an increase in size that was attributable to estuarine growth (Levy et al. 1979).

Chum

In the Pacific Northwest, juvenile chum have been found to feed on harpacticoid copepods, gammarid amphipods, and dipteran larva, pupae, and adults (with chironomids being the most common) (Salo 1991). Juvenile chum diets were reported to be highly taxa- and size-selective (Simenstad et al. 1982). Chum fed on epibenthic crustaceans (harpacticoid copepods, gammarid amphipods, and isopods) and insects (chironomids) in Washington estuaries (Simenstad et al. 1982). Congleton (1979) reported that juvenile chum residing in the Skagit River estuary fed primarily on Chironomidae pupae and adults, but oligochaetes, amphipods (*Anisogammarus confervicolis* and *Corophium salmonis*), and mysids (*Neomysis mercedis*) were also consumed. In the Nisqually River estuary, epibenthic harpacticoid copepods were the dominant prey item of small chum (29 mm - 70 mm in length), but as the fish grew (> 70 mm in length) and moved into the Nisqually Reach, the pelagic copepod (*Corycaeus*) became the dominant prey item (Pearce et al. 1982). Chum salmon from the Lower Fraser estuary were found to feed heavily on harpacticoid copepods (80% by total number) (Levy and Northcote 1981; Levings and Nishimura 1997). In the Nanaimo estuary, juvenile chum were found to feed (in decreasing order of importance) on harpacticoid copepods, decapod larvae, adult insects and calliopiidae (amphipoda) (Sibert et al. 1977; Healey 1982).

Chum foraging habits in restored intertidal wetlands appear to be similar to chum occupying "natural" habitat. Chum at Spencer Island, Washington (a breached dike site) consumed mainly chironomid pupae and adults, and some mysid shrimp (*Neomysis mercedis*) (Cordell et al. 1998).

Wild chum salmon used Yaquina Bay for rearing as indicated by an increase in size of resident fish (Myers and Horton 1982). Levy and Northcote (1982) found evidence of estuarine growth in juvenile chinook and chum salmon, with chinook showing the most growth; in contrast, they found no evidence of growth in pink salmon captured at the Fraser River estuary. Healey (1982) reported that chum fry grew approximately 5.7% of their body weight per day in the Nanaimo estuary.

Pink

Pink salmon are both generalists and opportunists, preying on both pelagic and epibenthic organisms, and they appear to be diurnal feeders (Heard 1991). Juvenile pink salmon fed on neritic zooplankton (calanoid copepods, copepod nauplii, and larvaceans) in Washington estuaries (Fresh et al. 1979; Simenstad et al. 1982). Pink salmon fed on harpacticoid copepods and amphipods in the Nanaimo estuary and calanoid copepods in the Fraser River estuary (Healey 1982).

Juvenile pink salmon captured at the inner Fraser River estuary showed no increase in size with time (Levy et al. 1979; Healey 1982).

Coho

Wild and hatchery coho smolts from Yaquina Bay fed on juvenile fish, primarily anchovy (*Engraulis mordax*), surf smelt (*Hypomesus pretiosus*), and sand lance (*Ammodytes hexapterus*) and on crustaceans, primarily crangoid shrimp and megalopa larvae of Dungeness crab (*Cancer magister*) (Myers 1979). While in the estuary, the diet of Columbia River coho smolts was dominated by the amphipod *Corophium salmonis*; other major food items were Diptera, Homoptera, and *Cancer* megalops (Durkin 1982). The percentage of stomachs containing food ranged from 75% to 95%, site and date dependent, and indicated coho smolt utilization of the estuary (Durkin 1982). Coho rearing in Washington estuaries preyed on large planktonic or small nektonic organisms, such as decapod larvae, larval and juvenile fish and euphausiids, in addition to drift insects and epibenthic gammarid amphipods (Simenstad et al. 1982). The dominant prey item of juvenile coho using the Nisqually River estuary was sand lance (Pearce et al. 1982). In the Nanaimo estuary coho fed on fish larvae, decopod larvae, and larval insects (Healey 1982).

Food habits of coho in restored intertidal wetlands appear to be similar to coho occupying "natural" wetlands. Cordell et al. (1998) reported that coho fed mainly on chironomid pupae and adults, as well as surface-drift organisms (beetles, flies, and spiders) and a benthic fresh water isopod (*Caecidotea*) at Spencer Island, Washington.

Juvenile coho in the Nanaimo estuary grew approximately 1.5% of their body weight per day, which is approximately a quarter of the growth rates seen for chinook and chum, and indicates much less estuarine utilization than chinook and chum (Healey 1982). Tschaplinski (1982) reported that coho rearing in the Carnation Creek estuary on Vancouver Island, on average, grew 1.8 to 2.3 times faster on a monthly basis than their respective stream-rearing conspecifics.

Sockeye

Sockeye rearing in northern Puget Sound estuaries fed on juvenile shrimp, euphausiids, and decapod larvae (Simenstad et al. 1982). Sockeye fed on cladocera, decapod larvae, ostracods, adult insects, amphipods, and calanoid copepods in southern British Columbia estuaries (Healey 1982).

Food habitat studies from Bristol Bay indicate that yearling sockeye use the inner bays very little (as evidenced by empty stomachs) and scale studies show little marine growth until the smolts had been at sea for at least four to six weeks (Burgner 1991).

Interspecific Comparisons

Healey (1982) concluded that juvenile anadromous salmonid diets vary among times of sampling, habitats within an estuary, and different estuaries. He also concluded that juvenile salmonids are opportunistic and can feed on a variety of taxa. Chinook, which exhibit the greatest dependence on estuaries, have a more diverse estuarine diet than coho and chum, which are less dependent on estuaries and have a more specialized estuarine diet (Healey 1982; Pearce et al. 1982; Simenstad et al. 1982). There also appears to be an affinity, by all salmon species, for benthic food items while residing in the upper estuary as fry, which then changes to pelagic food items as salmon grow and move to deeper water with higher salinity (Healey 1982; Macdonald 1987; Wissmar and Simenstad 1988).

Detrital-based Food Webs

In addition, many of the benthic food items that salmon fed on are dependent on detritus for food. Therefore, a link could be made between salmon production and the detritus-based food web (Sibert et al. 1977; Sibert 1979; Healey 1982; Shreffler et al. 1992). As shown above, estuaries are very important in providing forage for juvenile anadromous salmonids. Juvenile chinook and chum salmon residing in estuaries are dependent on benthic organisms (harpacticoid copepods) which are, themselves, dependent on detritus (Sibert et al. 1977; Sibert 1979). The major source of detritus for this food web in the Nanaimo estuary is terrestrial organic material from the upper watershed which is transported to the estuary via the Nanaimo River; in addition both *Zostera* and *Carex* meadows, and algae from intertidal areas are also seasonal detritus sources (Sibert et al. 1977; Naiman and Sibert 1979). Healey (1982) reported that juvenile salmonids tend to congregate in areas where estuary morphology favored detritus retention, such as weed beds, and channels with braided and meandering morphology. He also reported that salt marshes are good detritus traps, in addition to being highly productive areas for juvenile salmon food items.

Physiological Transition

During migration, anadromous salmonids must transition from retaining salts and excreting water in fresh water (a salt poor environment) to excreting salt and retaining water in salt water (a salt rich environment). The physiological mechanisms for the transition from fresh to salt water include an increase in chloride cells, gill Na^{+}-K^{+} ATPase activity, membrane permeability, and drinking rate (McCormick 1994). In addition, anadromous salmonids become more streamlined and take on a silvery appearance (Hoar 1976). Although the basic physiological mechanisms are similar for all species of salmonids, there are interspecific differences in what controls the physiological transition. In salmon that enter the estuarine environment as fry soon after emergence, such as pink, chum, and ocean-type chinook, internal (ontogenetic) information may control the physiological transition (McCormick 1994). In salmon that enter the marine environment as smolts one to two years after emergence, such as coho, sockeye, and stream-type chinook, environmental factors like changes in photoperiod, water temperature, and salinity may control the physiological transition (Hoar 1976; McCormick 1994).

Due to the complex physiological transition from fresh to salt water, juvenile salmonids may benefit from the gradual transition in an estuarine environment (Simenstad et al. 1982). Estuaries are important as both staging and rearing areas for juvenile salmon. Wild coho were reported to use Yaquina Bay as a staging area, as indicated by short residence times and lack of an increase in size (Myers and Horton 1982). Moser et al. (1991) reported that tagged coho smolts actively swam against ebbing tides in order to hold for extended times at the mouth of the Chehalis River in Washington. Both experimental and field results concluded that estuaries in Japan are important for physiological transition in chum fry (Iwata and Komatsu 1984). Healey (1982) concluded that all five salmon species use estuaries for physiological transition, but only pink and sockeye salmon use estuaries solely for this purpose.

Refugia

The complex and dynamic morphology of estuarine habitat may provide refugia for juvenile salmonids from high flows and predators. The mosaic of distributary channels draining an estuary may protect young fish from being swept downstream by high river flows or tidal currents (Levy et al. 1979). High flow refugia are also created by large logs and rocks, which provide juvenile fish microhabitats with reduced current velocity and back-eddies (Macdonald et al. 1987). Vegetation associated with estuarine marshes may provide juvenile salmonids with cover to avoid predators (Dorcey et al. 1978; Simenstad et al. 1982; Levings and Nishimura 1997). The high turbidity of some estuaries may also protect juvenile salmonids from visual predators (Simenstad et al. 1982). Gregory and Levings (1996) showed that, under laboratory conditions, predation by cutthroat trout on juvenile salmonids was significantly reduced in the presence of vegetation. Stomach analysis showed that predatory fish (chinook smolts and large staghorn sculpins) had a negligible impact on juvenile salmonids in the Fraser River estuary (Levy et al. 1979).

Salmonid Utilization of Restored or Created Estuaries

In a study of the lower Fraser River estuary, Levings and Nishimura (1997) conducted an ecological comparison of reference (undisturbed), restored (revegetated), and disturbed (unvegetated) sites using a variety of ecological variables to determine whether restored marsh habitat functions (ecologically) as well as undisturbed natural marsh habitat. They found that invertebrate abundance was greater at reference and restored marsh sites than at disturbed sites and, in some cases, invertebrate abundance was higher at restored sites than at reference sites. These investigators also found that there was no significant difference in chinook and chum salmon fry abundance among reference, restored, and disturbed marsh sites. They did find a significant difference in chinook salmon and sockeye salmon smolt abundance among the three marsh sites, with higher catches in the disturbed marsh sites. Levings and Nishimura (1997) found that marked chum fry stayed in restored sites as long as at reference sites. The species composition of fish in a restored site was also similar to a reference site (Levings and Nishimura 1997). Juvenile anadromous salmonids did use the restored estuarine habitat, but the authors recommended that protecting natural estuarine habitat is preferable to mitigating the destruction of natural habitat with restored disturbed habitat.

Shreffler et al. (1990) reported significant chinook and chum fry usage of a restored marsh site in the Puyallup River estuary. Individual residence times at the restored marsh site ranged from 1 to 9 days for chum and 1 to 43 days for chinook. It was also determined that the juvenile salmonid forage was detritus based (Shreffler et al. 1992), therefore availability of allochthonous detritus should be considered in any restoration effort. Miller and Simenstad (1997) found no difference in growth rates between sub-yearling coho utilizing a created and natural estuarine slough on the Chehalis River, but invertebrate densities and stomach fullness indices were both lower in the created slough. Cordell et al. (1998) reported considerable juvenile chum salmon utilization of a restored marsh in the Snohomish River estuary, although no comparison to a "natural" reference site was conducted at that time.

Anthropogenic Effects

Human activity occurring within the estuary, as well as throughout the corresponding watershed can negatively affect juvenile anadromous salmonids utilizing estuaries. In addition, these anthropogenic effects on fish are compounded, in the estuarine environment, due to the added physiological stresses of the fresh water to marine transition (Varanasi et al. 1993; Waldichuk 1993). These activities include: 1) loss of intertidal rearing habitat due to structural development, training walls, shoreline armoring, jetties, dredging and filling, and beach graveling and predator exclusion nets as used in the intertidal aquaculture industry (Levings 1980; Waldichuk 1993; Thom et al. 1994; Simenstad and Fresh 1995); 2) decrease in dissolved oxygen due to input of sewage, agricultural practices, and dredging of anoxic sediments (Waldichuk 1993); 3) creating a toxic condition due to toxic chemical spills and the discharge of chemical waste from industry and mining (Waldichuk 1993); and 4) an increase in suspended solids due to logging activities upstream, agriculture practices, dredging, and input of sewage and industrial waste (Waldichuk 1993). The magnitude of anthropogenic effects on juvenile anadromous salmonids is dependent on the spatial, temporal, and intensity scales at which they occur (Simenstad and Fresh 1995).

Levy and Northcote (1981) concluded that juvenile anadromous salmonids utilize the entire length of tidal channel habitat in the Fraser River estuary, and any diking of that habitat would reduce the rearing capacity of the estuary. Training walls and jetties can alter the penetration of the salt water wedge into an estuary, the directional flow of the corresponding river, and the movement and distribution of allochthonous organic materials in an estuary (Levings 1980). These effects can cause shifts in biotic communities, reductions in juvenile salmonid prey resources, changes in migratory behavior, and loss of rearing habitat (Levings 1980; Waldichuk 1993; Thom et al. 1994; Simenstad and Fresh 1995).

Varanasi et al. (1993) looked at the effects of chemical contaminants on outmigrating juvenile chinook salmon in Puget Sound. Salmon utilizing "polluted" urban estuaries were compared to those utilizing "unpolluted" nonurban estuaries. Analysis of stomach contents for selected aromatic and chlorinated hydrocarbons indicated that juvenile chinook salmon utilizing urban estuaries demonstrated a greater exposure to chemical contaminants than fish utilizing nonurban estuaries. The authors also reported that immune dysfunction, reduced survival, and possible reduced growth of juvenile chinook were concomitant with increased exposure to chemical contaminants. This study found a significant route of sediment-associated contaminant exposure in short-term resident, pelagic fish (juvenile chinook salmon) via their benthic prey base.

Estimating the Salmon Productivity and Use of Estuaries

Juvenile salmonid utilization of the Skagit River estuary was estimated in 1979 and 1995. Congleton et al. (1982) computed that approximately 3.1 million chum fry and 1.1 million chinook fry reared in the Skagit River "salt marsh habitat" in 1979, which was approximately onethird of all downstream migrants of each species. In 1995, approximately 800,000 chinook (age 0+) reared in the Skagit estuary, which was approximately one-half of the total estimated chinook emigration that year (Hayman et al. 1996). The remaining half of the 1995 Skagit River chinook production reared in the fresh water habitats of the upper watershed.

Using an estimated abundance, average weight, and growth rate, Healey (1982) calculated annual salmon production (sum of daily biomass × instantaneous growth rate) of chum, chinook, and coho salmon for the Nanaimo estuary, which consists of 2 km^2 of intertidal marshes, 6.5 km^2 of intertidal sand flat, and 3 km^2 of subtidal basin. He calculated a total annual juvenile salmon production of approximately 2000 kg, which included 1750 kg of chum, 200 kg of chinook, and 49 kg of coho. Levy and Northcote (1981) estimated that the Fraser River estuary was utilized by millions of juvenile chinook salmon during one season.

In a small system (Carnation Creek, Vancouver Island), Tschaplinski (1987) estimated the net coho production (increase in biomass) during May to September for 1979 and 1980. The net coho production for 1979 was 34 kg, of which 20% was estuarine-derived and 80% was freshwater-derived. The net coho production for 1980 was 37 kg, of which 27.5% was estuarine-derived and 72.5% was freshwater-derived. Therefore, estuaries can be important to coho production in some cases.

Species-Specific Differences in Estuarine Utilization

Dorcey et al. (1978) and Healey (1982) concluded that, among anadromous salmonids, chinook were the most dependent on estuarine habitat with chum, coho, sockeye and pink salmon following (in decreasing dependency). Simenstad et al. (1982) concluded that juvenile chinook and chum salmon were the major salmonid users of estuaries. An assessment of primary critical habitat issues affecting chinook salmon in fifteen Washington watersheds concluded that estuarine loss was a limiting factor in fourteen of the watersheds (Bishop and Morgan 1996). Spatial and temporal (both individual and as a species) utilization of estuaries by juvenile salmonids are described below.

Spatial Utilization

Chum fry residing in the Skagit River estuary fed most intensely in upper salt marsh during high tide (Congleton 1979). Using estimated production of juvenile chinook in the Skagit estuary, Hayman et al. (1996) reported that 60% came from emergent/forested transition (high elevation intertidal), 36% from estuarine emergent marsh (salt marsh), and 4% from forested riverine /tidal (tidally influenced river) habitat zones. The most productive habitat types within the zones were small and large blind channels (Hayman et al. 1996). In Commencement Bay, Washington, a highly degraded estuary, juvenile anadromous salmonids utilized intertidally exposed mudflats and corresponding shallow water habitat (Miyamoto et al. 1980).

Sampling of neritic habitat at the outer edge of the Nisqually Delta, Washington, indicated that juvenile chinook and chum salmon were the most abundant salmonid in 1977; the habitat sampled was tidal mudflat with a moderate slope (Fresh et al. 1978, 1979). In 1979 and 1980, sampling of the upper and lower Nisqually estuary indicated that juvenile chinook and chum salmon were the most abundant and widely distributed salmonids throughout the estuary; the fish utilized marsh sloughs, channels, and the nearshore habitats of the Nisqually Reach (Pearce et al. 1982).

Using factor analysis, Levy and Northcote (1981) found that chinook and chum fry and chinook smolts were positively associated with large tidal channels and negatively associated with small low-elevation tidal channels in the Fraser River estuary. Levy and Northcote (1982) found juvenile chinook, chum, and pink salmon to be common in the tidal channels of the Fraser River estuaries with chinook salmon being the most abundant. Coho salmon smolts and sockeye salmon fry and smolts occurred in the tidal channels, but in much smaller numbers than chinook, chum, and pink salmon. Based on mark-recapture results, chinook fry rearing in the Fraser River estuary showed a high degree of fidelity to specific tidal channels (Levy et al. 1979). Juvenile chinook did not appear to distributionally segregate according to size within a tidal channel in the Fraser River estuary (Levy and Northcote 1981).

The following are the most significant results of a stepwise multiple regression analysis of fish catch data (7 fish species as dependent variables) and tidal channel habitat data (15 measured characteristics as independent variables) from the Fraser River estuary (Levy and Northcote 1981). Chinook smolt catches were positively related to total tidal channel area (as defined by the 0-foot geodetic contour); chinook fry catches were positively related to area of low-elevation refuge (area of tidal channels retaining water at low tide) and negatively related to bank elevation (the absolute elevation of surrounding marsh habitat above 0-foot geodetic elevation); and chum fry catches were also positively related to area of low-elevation refuge and negatively related to average angle (in degrees) of the sedge bank (the relative slope of the tidal channel banks).

Tschaplinski (1982, 1987) reported that the majority of coho fry inhabiting the Carnation Creek estuary on Vancouver Island preferred low velocity sites, both main and side channel sites, and deep pools with salinity ranging from 0 to 19 ppt. The author reported coho fry densities up to 5 fry/m^2 in habitats containing the following at low tide: 1) low-velocity water averaging 8.7 cm/s and ranging from 0-32 cm/s; 2) pools usually 45-225 cm deep; and 3) cover such as undercut banks, overhanging vegetation, and large woody debris.

In summary, juvenile anadromous salmonids generally preferred estuarine habitats that were vegetated, heavily channelized with a moderate slope, and which offered a wide range of water salinities. This habitat provided low-water-velocity refugia at low tide; cover in the form of vegetation and large woody debris; and a good prey base.

Temporal Utilization (Individual)

Individual juvenile chinook fry resided for two months in the Sacramento-San Joaquin River estuary and began emigrating at a fork length of 70 mm (Kjelson et al. 1982). Estimated resident times for chinook in Washington State estuaries range from 1-189 days (Simenstad et al. 1982; Shreffler et al. 1990). Healey (1980) estimated that individual juvenile chinook salmon reared an average of 25 days in the Nanaimo estuary and emigrated after reaching 70 mm in fork length.

Estimated resident times for individual juvenile chum in Washington State estuaries range from 1-32 days, with 30-32 days being most common (Simenstad et al. 1982; Shreffler et al. 1990). Individual chum salmon spent up to three weeks rearing in the Fraser and Nanaimo River estuaries, and movements in and out of these estuaries were correlated with the tides (Healey 1982; Salo 1991). Healey (1979) estimated that chum resided in the Nanaimo estuary from 0 to 18 days.

Individual pink salmon fry resided in the marsh area of the Fraser River estuary no more than a day or two before emigrating (Levy et al. 1979).

Individual wild coho salmon may reside in estuaries from a few days to a few weeks (Myers 1979). Estimated resident times for coho in Washington State estuaries range from 6-40 days (Simenstad et al. 1982).

Temporal Utilization (Species)

Peak time for chinook fry occupation of estuaries ranges from January to May, depending on latitude and annual variation (Healey 1991). Peak chinook salmon fry rearing in the Sacramento-San Joaquin estuary occurred from February to March (Kjelson et al. 1982). Chinook salmon were present in Yaquina Bay, Oregon during nine months (January and April-November) and peaked from mid July to early August (Myers and Horton 1982). Estimated species resident times for chinook salmon in Washington State estuaries ranges from 6-29 weeks (Simenstad et al. 1982). Juvenile chinook occupy the Skagit River estuary from March to May (Congleton 1979). Peak juvenile chinook utilization of the Nisqually River estuary occurs from early May to late July (Fresh et al. 1979; Pearce et al. 1982). Chinook fry were residents of the Fraser River estuary from March to June (Levy and Northcote 1981).

Chum salmon were present in Yaquina Bay, Oregon for 2-3 months between March and June, and their numbers peaked in early April (Myers and Horton 1982). Estimated species resident times for chum salmon in Washington State estuaries ranges from 5-23 weeks (Simenstad et al. 1982). Juvenile chum occupy the Skagit River estuary from March to May (Congleton 1979). Peak juvenile chum utilization of the Nisqually River estuary occurs from late April to late June (Fresh et al. 1979; Pearce et al. 1982). Chum fry were abundant in the Nanaimo estuary from April to June (Healey 1982).

Pink fry were reported to inhabit the tidal marshes of estuaries at high tide and leave on the first ebb tide (Healey 1982). Estimated species resident times for pink salmon in Washington State estuaries range from 4-18 weeks (Simenstad et al. 1982). Pearce et al. (1982) reported minimal usage of the Nisqually River estuary by juvenile pink salmon, but utilization of the Nisqually Reach occurs from March to June, peaking from the end of March to mid April (Fresh et al. 1979). Levy and Northcote (1982) reported pinks to be abundant, but transient, in the Fraser River estuary. Pink salmon were found feeding for up to two months in an Alaskan estuary (Heard 1991).

Levy and Northcote (1982) found an abundance of juvenile chinook salmon, chum salmon, and pink salmon in tidal channels of the Fraser River estuary between March and June 1978. Chinook and chum salmon may be residents, returning on several tide cycles, with chinook salmon residing in the estuary the longest, up to one month.

Wild coho salmon smolts were present in Yaquina Bay, Oregon for 2-3 months between March and June, and peaked in mid May (Myers and Horton 1982). Migrating coho smolts were present in the Columbia River estuary for six weeks (late April to early June) and peaked early to mid-May (Durkin 1982). Estimated species resident times for coho salmon in Washington State estuaries ranges from 5-15 weeks (Simenstad et al. 1982). Ocean-type juvenile coho utilized estuarine habitat from March to October at Carnation Creek on Vancouver Island (Tschaplinski 1982, 1987).

Estimated species resident times for sockeye salmon in Washington State estuaries was 12 weeks (Simenstad et al. 1982). Fraser River sockeye fry reared in the estuary from April to June (Healey 1982). Juvenile sea-type sockeye rear in the Situk River estuary in Alaska for three to four months before migrating to the ocean at a length of at least 50 mm (Gustafson 1997).

Simenstad et al. (1982) or Johnson et al. (1997) provide an excellent tabular summary of juvenile chum, pink, coho, and chinook salmon residence times in Washington State estuaries.

Four possible factors have been suggested as limiting the residence time of juvenile salmonids in estuaries: 1) an increase in summer water temperature (Healey 1980; Kjelson et al. 1982); 2) availability of preferred prey (Healey 1979; Simenstad et al. 1982); 3) river discharge and surface outflow (Levy and Northcote 1981; Simenstad et al. 1982); and 4) density-dependent interactions among juvenile fish (Levy and Northcote 1981).

Simenstad et al. (1982) addressed adult salmon (pink, coho, chum, chinook, and sockeye) utilization of estuaries in Washington State and found that adult salmon occupied estuaries every month of the year, although July through September were the peak times. They also estimated individual adult salmon residence time, which ranged from one to six weeks. In some cases, pink and chum salmon have also spawned in the intertidal zone (Meehan and Bjornn 1991).

Hatchery Component

Wild chum juveniles emigrate from Hood Canal at different rates and times of year than hatchery chum salmon (Salo 1991). Myers' and Horton's (1982) data suggest that interspecific temporal partitioning of the estuarine habitat by wild juvenile salmonids (chinook, coho, and chum salmon) should be considered when managers are determining release dates for hatchery fish in order to decrease competition with wild fish in estuaries. Hatchery coho salmon were found to reside longer (a few even overwintered) in Yaquina Bay than wild coho (Myers and Horton 1982). Myers (1979) showed that, site dependent, hatchery coho and wild coho smolts' diets may range from a high degree of similarity to almost no similarity, and with similarity in diet there is the potential for competition between hatchery and wild fish. Myers (1979) also concluded that juvenile wild chinook salmon may have the greatest potential for competition with cultured juvenile salmonids due to the chinooks' dependence on estuaries and their extended estuarine rearing period. Resource partitioning (Schoener 1974) appears to take place in a "natural" estuarine system in order to reduce inter- and intraspecific juvenile salmonid competition (Myers and Horton 1982; Thorpe 1994). Therefore, if the goal of a restoration effort is to increase "wild" anadromous salmonid estuarine production, then the hatchery component should be accounted for in order to offset any possible losses due to competition between wild and hatchery fish.

Restoration

Levings and Nishimura (1997) concluded that it was better to save estuarine habitat than to try to mitigate for loss of it later, but that estuary restoration is beneficial in correcting past destruction of estuarine habitat. These authors also suggested that more evaluation of estuarine restoration and mitigation projects is needed. However, evaluation of restoration projects is difficult due to the dynamics of tidally influenced areas and the daily and seasonal variation that accompanies these dynamic systems. Simenstad et al. (1991) is a good source of information on protocols and techniques for estuarine habitat assessment.

When planning a restoration project, Beechie et al. (1996) recommend focusing on restoring habitat-forming processes and function, and ranking the restoration actions to meet a specified recovery goal. Fish entrapment is a critical issue that should be addressed during the planning of any estuarine restoration project. Proposed projects should be designed to reduce any pooling of water and possible entrapment of fish at low tide because juvenile salmon are very sensitive to water temperature and dissolved oxygen levels. Water temperature tolerances are dependent on the species of fish, the size of fish, and the salinity of the water. In general, the lethal minimum and maximum water temperatures for juvenile Pacific salmon are 0°C and 25°C, respectively (Piper et al. 1982; Waldichuk 1993). Juvenile chinook and coho are the most resistant to high temperatures with sockeye, pink, and chum following (in decreasing resistance) (Waldichuk

1993). Dissolved oxygen levels decrease with an increase in water temperature or salinity. Salmon prefer dissolved oxygen levels of 5 ppm or greater (80% or greater O_2 saturation) (Piper et al. 1982; Waldichuk 1993).

Creating habitat which favors predators of juvenile anadromous salmonids should be avoided when planning a project. Miller and Simenstad (1997) reported a more diverse fish community and a higher density of potential predators (yearling coho, northern squawfish (*Ptychocheilus oregonensis*), and steelhead) at a created estuarine slough than at the reference site, a natural estuarine slough. The created site had greater depth and width, and increased submergence time and range of water salinity than the reference site. These factors favored potential salmonid predators. The authors also reported that juvenile salmonids residing in the created slough had significantly lower indices of stomach fullness than cohorts residing in the natural slough. The lower indices suggest that an increase in predator density may restrain normal juvenile salmon feeding behavior (Miller 1993).

SUMMARY

Estuaries provide important rearing habitat for all five species of salmon reviewed in this report, but juvenile chinook and chum salmon appear to be the most estuarine-dependent species. Juvenile salmonids residing in estuaries prefer shallow salt marsh habitat at high tide and flowing tidal channels at low tide, but move into the neritic zone and become more pelagic as the fish increase in size. Estuaries also provide physiological transition or staging sites for both juvenile and adult salmon, but this function is observed most often in pink and sockeye fry. The importance of estuaries as refugia is implied in many studies, but little research has looked directly at this function. As Meyer (1979) found, most current studies of estuarine utilization by juvenile salmonids are related to food habits, although there appears to be a shift to habitat-function research, which will better answer land management questions. The importance of detritus must not be overlooked in any restoration effort, due to its importance to juvenile salmonid prey. The cooperation of hatchery managers (timing of any releases) is also important to any estuarine restoration efforts, if increasing wild salmonid abundance is a restoration goal.

After reviewing the literature on juvenile salmonid use of estuaries, both Dorcey et al. (1978) and Meyer (1979) concluded that there is great variability among estuarine ecosystems and data from other estuaries must be reviewed carefully before being applied to a particular estuary. However, both authors stress that remaining estuaries in the Pacific Northwest must be protected due to their importance to anadromous salmonids, as well as to birds, mammals, and other marine fishes.

Summary Points

- Juvenile chinook and chum salmon are the most estuarine-dependent anadromous salmonids in the Pacific Northwest with coho, sockeye and pink salmon following (in decreasing dependency).

- Estuaries are very important to adult salmon for staging and physiological transition, and are also important to juvenile salmon for rearing, physiological transition, and refugia.

- Estuaries provide juvenile anadromous salmonids neustonic, pelagic, and benthic prey, some of which are dependent on a detritus-based food web.

- Estuaries provide both adult and juvenile anadromous salmonids a range of water salinties in which to transition, physiologically, from fresh to salt water or salt to fresh water.

- Estuaries provide juvenile anadromous salmonids refugia from high water flows and predators.

- In general, anadromous salmonids can be found in estuaries every month of the year, but peak abundance occurs from March to July for juveniles and July to September for adults.

- Juvenile chinook salmon are present in estuaries from January to November, latitude dependent, and peak abundance occurs from March to July. Individual juvenile chinook may reside in estuaries from 6 to 189 days.

- Juvenile chum salmon are present in estuaries from March to June, latitude dependent, and peak abundance occurs in May and June. Individual juvenile chum may reside in estuaries from 4 to 32 days.

- Juvenile coho salmon are present in estuaries from March to October, latitude dependent. Individual juvenile coho may reside in estuaries from 6 to 40 days.

- Juvenile sockeye and pink salmon are present in estuaries from March to June, latitude dependent, but are not considered long-term residents.

- Four possible factors have been suggested as limiting the residence time of juvenile salmonids in estuaries: 1) an increase in summer water temperature; 2) lack of preferred prey; 3) extreme (high or low) river discharge and surface outflow; and 4) density-dependent interactions among juvenile fish (i.e., an increase in antagonistic interactions).

- Juvenile anadromous salmonids generally prefer estuarine habitats that are vegetated (e.g., salt marsh), that are heavily channelized with a moderate slope, and that offer a wide range of water salinities. These habitats provide salmon low-water-velocity refugia at low tide; cover in the form of vegetation and large woody debris; and a good prey base.

- Restored estuarine marsh habitat is extensively used by juvenile anadromous salmonids, based on studies conducted in the Fraser and Puyallup River estuaries.

- Human activity (e.g., structural development, jetties, diking, dredging and filling, logging, pollution) occurring within a watershed and corresponding estuary can negatively affect juvenile anadromous salmonids utilizing estuaries. In addition, these anthropogenic effects on fish are compounded, in the estuarine environment, due to the added physiological stresses of the fresh water to marine transition.

- Resource partitioning appears to take place in a "natural" estuarine system in order to reduce inter- and intraspecific juvenile salmonid competition. Therefore, if the goal of a restoration effort is to increase "wild" anadromous salmonid estuarine production, then the hatchery component should be accounted for in order to offset any possible losses due to competition between wild and hatchery fish.

- Saving estuarine habitat is preferable to mitigating for the loss of it later, but estuary restoration is beneficial in correcting past destruction of estuarine habitat.

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